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MULTI-RESPONSE OPTIMIZATION OF PROCESS PARAMETERS OF GREEN ELECTRICAL DISCHARGE MACHINING ON AISI 2507 SUPER DUPLEX STAINLESS STEEL USING GREY RELATIONAL ANALYSIS (GRA)

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ABSTRACT

This research presents a performance analysis and investigation on eco-friendly Pongamia green dielectric (GD) with a pure copper tool electrode in the electrical discharge machining (EDM) of AISI 2507 super duplex stainless steel. The multi-response optimization of the EDM process parameters like pulse-on time (T_{ON}), pulse-off time (T_{OFF}), peak current (I_P), voltage (v) and inter-electrode gap (IEG) on the material removal rate (MRR), electrode wear rate (EWR) and surface roughness (SR) on the EDM of AISI 2507 super duplex stainless steel using grey relational analysis was examined. The Taguchi's design based L_{27} orthogonal array (OA) was employed for experimentation, and then investigated the optimal levels with grey relational analysis (GRA). Experimental results were analyzed statistically by analysis of variance. Surface and sub-surface cracks are analyzed by scanning electron microscopy. The optimal levels achieved by GRA were T_{ON}=400µs, T_{OFF}=60µs, I_P=21A, v=50V, and IEG=60µm.

KEYWORDS: Green Dielectrics, EDM, Surface Roughness, MRR, EWR & Grey Relational Analysis

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INTRODUCTION

Electrical discharge machining (EDM) is a well-established unconventional machining process, which has an extensive use in processing the precise and intricate geometries, particularly in the tool and die-making manufacturing for of its adaptability and its capability to machine high hardened steels and alloys [1]. The EDM process engages a series of intermediate high-frequency intermediate electric spark discharges owing to thermo-electric ionization of the applied dielectric fluid. Plasma accumulated in the process, increase the temperature in the range of 8000 to 12,000 K, which will result in melting and vaporization the work surface material [2].

AISI 2507 super duplex steel is intended for the applications which claim excellent strength and resistance to corrosion. Alloy 2507 possesses 24-25% chromium, 4.2-5% molybdenum, and 6.5-7% nickel. This high content of chromium, molybdenum, and nitrogen composition consequences in exceptional resistance to seawater chloride pitting and crevice-corrosion occurrence and moreover structure of 2507 with remarkable resistance to stress corrosion cracking in chloride environments. Duplex 2507 possesses excellent mechanical properties. Habitually a light device of 2507 materials can be to attain the similar design strength of a denser nickel-based alloy. Conversely, reduced machinability via the conventional mechanical cutting processes, consequences in increased tooling overheads [3]. EDM is an extremely energy concentrated process which devours 30–50 times greater energy

than in conventional machining. In addition, EDM yields very low machining rates as compared to that of conventional machining processes [4]. The option to reduce the consumption of energy brands the production costs tremendously attractive in terms of safeguarding the environment. Though, this general certainty that the small and micro level scale suggests a greater sustainability as matched to traditional manufacturing processes, modern research discloses that certain factors can make the manufacturing practices for additional manufacturing process costs and environmental burdens [5]. The discarding of waste produced in the machining process like tiny debris particles mixed with dielectric fluid, blocked and spoiled filters, consumed tool-electrode materials result in severe issues associated with repeatability, reuse, recycle. Hydrocarbon-based Dielectric fluids are concerned more towards high volatility and flammability [6]. The EDM process results in severe occupational and personal health safety concerns owing to the discharge of toxic aerosol emissions and odor, and tiny charged Nanoparticles, and even constant exposure to the contaminated working region [7]. Decay and decomposition of hydrocarbon formulated dielectric fluids and water based other aqueous dielectric fluid solutions result in excessive carburization, oxidation, corrosion, fatigue, and formation of microcracks with Heat affected zone [8].

Bio-based natural esters (green dielectrics) conquests over conventional hydrocarbon-based dielectric as these green dielectrics have enhanced physical and thermal properties like higher flashpoint, higher viscosity, and exceptional biodegradability. The more oxygen presence and higher dielectric breakdown voltage (BDV) delivers fewer toxic emissions and in general to be considered as eco-friendly [9]. To alter the non-edible Pongamia oils into the green dielectric, the oil has to be initially tested for moisture content prior subjected to titration process. The Titration procedure is important in order to decide the volume of the applied catalyst in the process. The applied catalyst (Sodium hydroxide) and concentrated methanol solution are mixed with the Pongamia oil. The Pongamia oil will experience a trans-esterification process (reaction process), result in the reaction of triglycerides with solute methanol to result in a combination of of fatty acid methyl esters (green dielectric) and soap (glycerin) [10]. The Pongamia green dielectric (GD) can be now applied as potentially alternate dielectric fluid in machining process whereas the glycerin is processed into soap. The derivatives of trans-esterification are not hazardous and can be decomposed certainly with ease. This styles the EDM process as eco-friendly and sustainable [11].

Lin et al. [12] studied the influence of EDM process parameters on the performance features and noticed an intensification in the material erosion with the applied current. Pellicer et al. [13] investigated the effect of the different process parameters on the geometrical accuracies and aspects of dimensional tolerances in the µ-EDM process. Srivastava et al. [14] have noticed that the applied the pulse-on time and discharge current and were the key important factors affecting the surface roughness in the cryogenically treated environment. Pilligrin et al. [15] have reported that the process parameters optimization in the EDM as necessarily a multi-response task of optimization. Experiments were performed by drilling micro holes in EDM. Grey relational analysis (GRA) was engaged to decide the optimal process parameter combinations which satisfy the multiple performance characteristics of the EDM. A wide research has been conveyed on EDM, while some degree of work has been started on eco-friendly EDM. So eco-friendly dielectric application was nominated to drill blind-holes. AISI 2507 had a wide range of applications in marine and heat exchange, owing to which accurate holes are obligatory to drill. A blind-hole of 9.67 mm diameter is challenging to drill with conventional methods for hard materials. So, in the present investigation, AISI 2507 is machined with EDM in the presence of eco-friendly dielectric for accurate drilling and better surface integrity of the machined surface. No past, researchers have been published by AISI 2507 with an eco-friendly green dielectric with EDM till date.

MATERIALS AND METHODS

Experimental Set Up

The conduct of experiments was piloted on the ARD EDM ZNC Die-sinker EDM. The machine was tailored with a customized tank set up for the green dielectric supply. Experiments were performed on AISI 2507 super duplex stainless steel. The dimensions of workpiece 150mm×100mm×15mm were selected. Electrolytic pure grade, 99.71% copper rod of 25mm * 9.67 mm Ø was utilized as a tool-electrodes for the experimental trials. The properties of the applied dielectric in the machining process are listed in Table 1.

Process Parameters

There are several process parameters which govern the performance measures in the EDM. Pulse-on time (T_{ON}), pulse-off time (T_{OFF}), peak current (I_P), voltage (v) and inter-electrode gap (IEG) were selected as the variable parameters. Duty factor was maintained 75-95 % throughout the experimentation. The chemical composition of the workpiece was listed in Table 1. The material removal rate and electrode wear rate were calculated by equation (1) and equation (2) respectively.

$$MRR = \frac{Volume}{Time} mm^3/min \tag{1}$$

$$EWR = \frac{Weight\ of\ electrode\ after\ machining - Weight\ of\ electrode\ before\ machining}{Time * Density\ of\ tool\ electrode}. \tag{2}$$

Table 1: Properties of Pongamia Green Dielectric (GD)

Properties	Pongamia Dielectric (GD)
Flash Point(^{0}C)	102
Fire point(^{0}C)	107
Dielectric constant at 27^o C	3.42
Density(gm/cc)	0.885
Kinematic Viscosity of 40^0(cSt)	7.15
Carbon residue (%)	0.01
Breakdown voltage (Kv)	22
Oxygen content (wt%)	0.52
Thermal conductivity (W/m K)	0.072
Ash content (%)	0.16%

Experimental Design

The present investigation comprises 5 different parameters with three different levels of experimentation. The Taguchi's L27 orthogonal array (OA) was engaged to study the influence of process parameters on the machining process and their significant influence on the machining process. This implicates that with the minimum number of experimental trials the maximum research information can be attained.

Taguchi's technique assists to decrease the time and costs by decreasing the number of experimental trials. Therefore, the experimental trials were directed use Taguchi's L27 OA. The Taguchi's methodology, experimental plan for the EDM process parameters is listed in Table 2. The achieved results from the experimentation were listed in Table 3.

Table 2: Process Control Parameters and their Levels

Symbol	Control Parameter	Units	Level 1	Level 2	Level 3
T_{ON}	Pulse-on time	µs	300	400	500
T_{OFF}	Pulse-off time	µs	30	60	90
I_P	Peak current	Amps	9	15	21
V	Voltage	Volts	40	50	60
IEG	Inter-electrode gap	µm	60	120	180

Table 3: Experimental Plan for the Process Parameters and Results

Trail No.	T_{ON} (µ-s)	T_{OFF} (µ-s)	I_P (amp)	V (volts)	IEG (µ-m)	MRR (mm^3/min)	EWR (mm^3/min)	SR (µm)
1	300	30	9	40	60	8.851	0.882	7.109
2	300	30	15	50	120	11.341	0.937	10.605
3	300	30	21	60	180	13.615	1.233	9.434
4	300	60	9	50	180	10.578	1.046	7.229
5	300	60	15	60	60	12.110	0.955	7.689
6	300	60	21	40	120	14.947	1.211	9.391
7	300	90	9	60	120	11.897	0.965	6.711
8	300	90	15	40	180	15.320	0.884	8.171
9	300	90	21	50	60	17.598	1.543	9.559
10	400	30	9	40	60	19.593	0.688	7.739
11	400	30	15	50	120	24.134	0.771	10.918
12	400	30	21	60	180	29.795	1.404	12.158
13	400	60	9	50	180	18.007	0.599	7.823
14	400	60	15	60	60	26.028	0.640	10.678
15	400	60	21	40	120	32.385	1.638	11.361
16	400	90	9	60	120	16.595	0.506	8.598
17	400	90	15	40	180	22.215	0.221	11.286
18	400	90	21	50	60	26.299	0.857	12.228
19	500	30	9	40	60	18.242	0.669	9.309
20	500	30	15	50	120	27.195	0.464	10.103
21	500	30	21	60	180	29.031	1.191	12.993
22	500	60	9	50	180	18.564	0.395	7.774
23	500	60	15	60	60	21.514	0.538	10.357
24	500	60	21	40	120	25.106	0.668	10.228
25	500	90	9	60	120	17.299	0.246	8.421
26	500	90	15	40	180	21.811	0.282	9.214
27	500	90	21	50	60	24.399	0.694	11.764

Grey Relational Analysis

The multiple response features of eco-friendly EDM process can be simultaneously optimized by generating a single-response grey relational (GR) grade from different coefficients of output characteristics. A greater GR grade agrees to the best combination of optimal settings of machining process parameters for multiple responses [16]. The Taguchi's technique is a well-defined application in experimental planning and determining the key influential process and their suitable levels of machining. The total road map for the grey relational analysis (GRA) procedure is listed in Table 4. The complete multi-response optimization is comprised of following steps:

Step 1: Signal to noise (S/N) initially needs to be calculate for the ratios for connecting results of experiments by with the application of the equation (3) and equation (4).

Smaller-The-Better (STB) characteristics,

$$\eta = -10 \times \log \frac{1}{n} \sum_{i=1}^{n} y_i^2 \tag{3}$$

Larger-The-Better (LTB) characteristics,

$$\eta = -10 \times \log \frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_i^2} \tag{4}$$

In the present research, MRR is of 'Larger-the-better' type of response quality characteristic. Consequently, the equation (3) has been utilized to determine the S/N ratio responses of experimental results. In the present research, EWR and SR are of 'Smaller-the-better' type of response quality characteristic. Consequently, the equation (4) has been utilized to determine the S/N ratio responses of experimental results.

Step 2: Data pre-processing/ Normalization

Data pre-processing essentially converts all the data in the range of 0 and 1. In EDM, as coming to MRR it is the 'larger-is-better' concert quality characteristic and equation (5) is applied, while equation (6) is used for EWR and SR which has the 'smaller-is-better' performance quality type characteristic. The formulas for both the quality characteristics are represented in an equation number (5, 6):

Larger the better characteristic,

$$x_{ij} = \frac{y_{ij} - \min_j y_{ij}}{\max_j y_{ij} - \min_j y_{ij}} \tag{5}$$

Smaller the better characteristic,

$$x_{ij} = \frac{\max_j y_{ij} - y_j}{\max_j y_{ij} - \min_j y_{ij}} \tag{6}$$

where x_{ij}denotes the normalized response value after grey-relational computation.

y_{ij}represents thei^{th} experimental trial result in the j^{th} experimental trial.

Step 3: Generation of grey relational co-efficient (GRC)

The grey relational coefficient can be calculated according to equation GRC (ξ_{ij}) is computed with the application of the formula represented in equation (7),

$$\xi_{ij} = \frac{\min_i \min_j |x_i^o - x_{ij}| + \zeta \max_i \max_j |x_i^o - x_{ij}|}{|x_i^o - x_{ij}| + \zeta \max_i \max_j |x_i^o - x_{ij}|} \tag{7}$$

where, x_i^o denoted the ideal normalized response value of the i^{th} experimental result and ζ denotes the distinguishing coefficient, which is normally selected as 0.5.

Step 4: Generation of Grey Relational Grade (GRG)

The grey relational grade (GRG) is generated by taking the average of all the grey relational coefficients of measured GRC responses and it is computed by the formula given in equation (8),

$$\gamma_j = \frac{1}{m}\sum_{i=1}^{m} \xi_{ij} \tag{8}$$

where, 'γ_j' - denotes the grey relational grade of the j^{th} experiment and 'm' denotes the number of response performance quality characteristics [26].

RESULTS AND DISCUSSIONS

The influence of the several process parameters on the performance measures is investigated. Primarily, the normalization of the data is accomplished with pre-process the elementary data sequences in the normalized range of 0 and 1. This method is termed as the generation of grey relational grades. With the application of the equation (6) and equation (7), the grey relational coefficient (GRC) for every response and the grey relational grade (GRG) are computed. In the present research work, as weight is equally delivered to all of the occurred, responses, the distinguishing features "ξ" is generally chosen as

Table 5 represents the response table of grey relational grade (GRG) and the corresponding rank of each process parameter.

From Table 4, it can be witnessed that the trial no.15 has the highest respective grade amongst all the 27 experimental trials. Consequently, the factor levels conforming to experiment no. 15 is the optimal response solution, to acquire the optimal multipleresponse characteristics of higher MRR, lower EWR and lower SR.

Table 5 displays the mean response of grey relational grade (GRG) for individual factor levels. It is witnessed that the levels second level of the T_{ON}, the first level of T_{OFF}, the third level of IP and second level of v and the first level of IEG corresponds to the maximum level of grey relational grade (GRG) for the factors A, B, C, D, and E.

Table 4: Grey Relational Analysis

Trail No.	S/N Ratios			Normalization			Grey Relational Coefficients (GRC)			GFRG	Rank
	MRR	EWR	SR	EWR	SR	ROC	EWR	SR	ROC		
1	18.939	1.083	-17.036	0.000	0.691	0.087	0.333	0.618	0.354	0.435	26
2	21.093	0.559	-20.510	0.191	0.721	0.693	0.382	0.642	0.619	0.548	15
3	22.681	-1.824	-19.494	0.332	0.858	0.516	0.428	0.779	0.508	0.572	12
4	20.488	-0.396	-17.182	0.137	0.776	0.113	0.367	0.691	0.360	0.473	22
5	21.663	0.395	-17.717	0.242	0.731	0.206	0.397	0.650	0.386	0.478	20
6	23.491	-1.669	-19.454	0.404	0.849	0.509	0.456	0.768	0.504	0.576	11
7	21.509	0.303	-16.536	0.228	0.736	0.000	0.393	0.654	0.333	0.460	24
8	23.706	1.062	-18.246	0.423	0.692	0.298	0.464	0.619	0.416	0.500	17
9	24.909	-3.768	-19.608	0.530	0.970	0.535	0.515	0.943	0.518	0.659	6
10	25.842	3.241	-17.774	0.613	0.567	0.216	0.563	0.536	0.389	0.496	18
11	27.653	2.256	-20.763	0.773	0.624	0.737	0.688	0.570	0.655	0.638	7
12	29.482	-2.948	-21.697	0.936	0.923	0.899	0.886	0.866	0.833	0.862	3
13	25.109	4.445	-17.867	0.548	0.498	0.232	0.525	0.499	0.394	0.473	21
14	28.309	3.864	-20.570	0.832	0.531	0.703	0.748	0.516	0.627	0.630	8
15	30.207	-4.291	-21.108	1.000	1.000	0.797	1.000	1.000	0.711	0.904	1*

Table 4 : Contd.,

16	24.400	5.915	-18.688	0.485	0.413	0.375	0.492	0.460	0.444	0.466	23
17	26.933	13.101	-21.051	0.709	0.000	0.787	0.632	0.333	0.701	0.556	14
18	28.399	1.335	-21.747	0.840	0.676	0.908	0.757	0.607	0.845	0.736	4
19	25.225	3.489	-19.378	0.558	0.553	0.495	0.531	0.528	0.498	0.519	16
20	28.691	6.670	-20.089	0.865	0.370	0.619	0.788	0.442	0.568	0.599	10
21	29.257	-1.519	-22.274	0.916	0.841	1.000	0.856	0.758	1.000	0.871	2
22	25.373	8.062	-17.813	0.571	0.290	0.223	0.538	0.413	0.391	0.448	25
23	26.655	5.370	-20.305	0.685	0.444	0.657	0.613	0.474	0.593	0.560	13
24	27.996	3.496	-20.196	0.804	0.552	0.638	0.718	0.528	0.580	0.609	9
25	24.761	12.181	-18.507	0.517	0.053	0.344	0.508	0.346	0.432	0.429	27
26	26.774	10.987	-19.289	0.695	0.122	0.480	0.621	0.363	0.490	0.491	19
27	27.748	3.165	-21.411	0.782	0.571	0.850	0.696	0.538	0.769	0.668	5

The responses equivalent to the maximum GRG(Grey relational grade) for the input process factors are T_{ON}=400µs, T_{OFF}=60µs, I_P=21 A, v=50V, and *IEG*=60µm. The main effects plot for GRG is depicted in Figure 1. It is also noticed that from Table 5, the peak current (I_P) is the key influential process parameter trailed by the pulse-on time (T_{ON}) and pulse-off time (T_{OFF}). Whereas, voltage (v) and inter-electrode gap (*IEG*) are identified as the least influential factors in the process.

Table 5: Taguchi's Analysis for Grey Relational Grade

Level	T_{ON} (µs)	T_{OFF}(µs)	I_P (Amp)	*v* (Volts)	*IEG* (µm)
1	0.5301	0.6155*	0.4664	0.5759	0.5988*
2	0.6400*	0.5722	0.5556	0.6106*	0.5801
3	0.5771	0.5516	0.7173*	0.5528	0.5604
Delta	0.1178	0.0639	0.2509	0.0577	0.0384
Rank	2	3	1	4	5

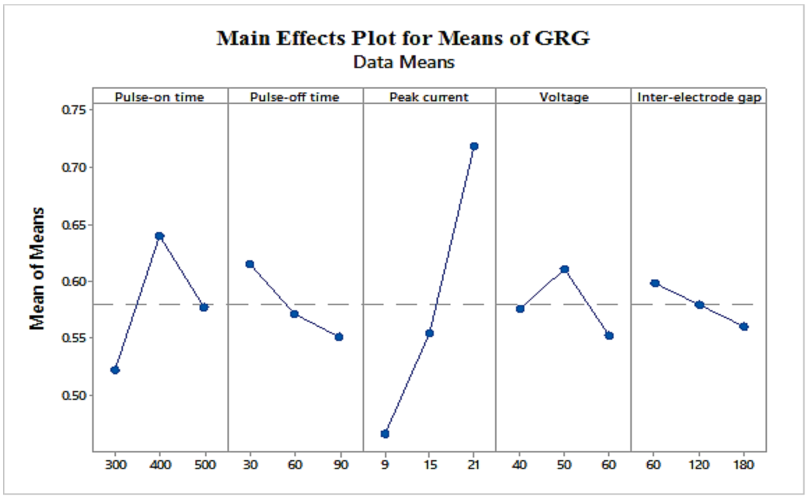

Figure 1: Main Effects Plot for the Grey Relational Grade (GRG)

Furthermore, a confirmatory experimental trial was performed to validate the influence of the optimal combination of input process parameters, and the attained results are listed in Table 6. The confirmatory experimental trial was performed by selecting the process parameters combination representing the maximum grey relational grade GRG (T_{ON}=400µs, T_{OFF}=60µs, I_P=21 A, v=50V, and *IEG*=60µm) acquired from Table 4. The predictions of the optimal levels are estimated by the equation (9).

$$\hat{\alpha} = \alpha_{mean} + \sum_{i=1}^{q}(\overline{\alpha_i} - \alpha_{mean}) \quad (9)$$

The results conforming to the process parameters, initial process parameter levels and the optimized process parameter levels are compared and listed in Table 6. Subsequently, the confirmatory experiment has been conducted to validate the multi-response optimization and the improvement in the performance characteristics measurement. The result from the optimal combination of process parameters settings, a confirmatory experiment is accompanied to authenticate the improvement of the multiple response characteristics. Then, the predicted response value is estimated using equation (9). The confirmatory experimental trials revealed that the GRG is greater for the optimal process conditions as compared to that of the initial process settings. The predicted GRG responses are in close in line with the experimented GRG results.

Table 6: Machining Performance Comparison of Initial and Optimum Process Settings

Levels	Initial Machining Process Variables Settings	Optimum Machining Parameters Settings	
	T_{ON}=300µs, T_{OFF}=30 µs, I_P=9A, v=40 V and IEG= 60µm	T_{ON}=400µs, T_{OFF}=60 µs, I_P=21A, v=50 V and IEG= 60µm	
		Predicted	Experimental
MRR (mm3/min)	8.850		32.385
EWR (mm3/min)	0.882		1.6389
SR (µm)	7.109		11.361
GRG	0.435	0.862	0.904
Improvement in GRG	0.469		

Statistical analysis is performed by analysis of variance (ANOVA) test is applied to measure the effect of every process parameter over the performance measures in response. In this investigation, the ANOVA test is piloted at the confidence level of 95% and at the 5% significance level. The ANOVA is performed using the grey-relation grades (GRG) responses, and the influence of the every process parameter over the performance measure is depicted in Table 7. Moreover, the contribution percentage of each process parameter over the output response is depicted in Table 7.

Table 7: ANOVA for GRG Responses

Source	DF	Adj SS	F-Value	P-Value	Percentage Contribution
T_{ON}	2	0.0625	7.24	0.006	13.47
T_{OFF}	2	0.0191	2.22	0.141	4.11
I_P	2	0.2912	33.73	0.000	62.78
V	2	0.0152	1.76	0.204	3.27
IEG	2	0.0066	0.77	0.480	1.42
Error	16	0.0690			14.87
Total	**26**	**0.4638**			**100**

S-0.657093 R^2-85.11%, R^2-adj-75.80, R^2-pred-57.59

CONCLUSIONS

In the present research, the pure electrolytic copper electrode was utilized as the tool-electrode and AISI 2507 super duplex stainless steel was utilized as the workpiece material, and the experimental trials were piloted with an eco-friendly green dielectric in the die-sinker EDM process. The process parameters were selected based on conducting the trial experiments. The experimentation process was directed by the Taguchi's L27 orthogonal array and later performing the experimental trials, the attained results for multiple responses were analyzed using grey relational analysis (GRA) technique to explore the optimal set of parametric combinations of the EDM process parameters to deliver the better quality results. Five process control parameters such as pulse-on time (T_{ON}), pulse-off time (T_{OFF}), peak current (I_P), voltage (v) and inter-electrode gap (IEG) varied each at three different levels. The following conclusions were reached :

- With the increase in pulse-on time (T_{ON}) increases, the electrode wear rate (EWR) of the material tend to decrease. The least electrode wear rate was noticed at 400 µs of the T_{ON}, 90 µs of T_{OFF}, 15 A of I_P, 50 Volts of v and 120 µm of IEG settings.
- The minimum response value of SR was measured as 6.711 µm at 300 µs of the T_{ON}, 90 µs of T_{OFF}, 9 A of I_P, 60 Volts of v and 120 µm of IEG settings.
- The multi-response optimization engaged with GRA is conducted and the optimal level of the process parameter settings was noticed to be 400 µs of the T_{ON}, 60 µs of T_{OFF}, 21 A of I_P, 50 Volts of v and 60µm of IEG for simultaneous optimization results of all three performance measures. The achieved results are validated by the confirmatory experimental trials.
- A confirmatory experimental trial was performed to authenticate the attained outcomes of the optimal parameter combination settings. The predicted optimal grey grade was noticed to be a closer in coincidence to the experimental attained grey relational grade for the optimal set of process parameters.
- Analysis of variance (ANOVA) analysis was measured, and the peak current (62.78%) was noticed as the key influential process parameter trailed by the pulse-on time (13.47 %).

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